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European Patent Office
Office européen des brevets



(11) Publication number:

0 405 757 A2

(12)

EUROPEAN PATENT APPLICATION

(21) Application number: 90305903.8

(51) Int. Cl.⁵: H01L 33/00

(22) Date of filing: 31.05.90

(30) Priority: 27.06.89 US 372275

(43) Date of publication of application:
02.01.91 Bulletin 91/01

(84) Designated Contracting States:
DE FR GB IT

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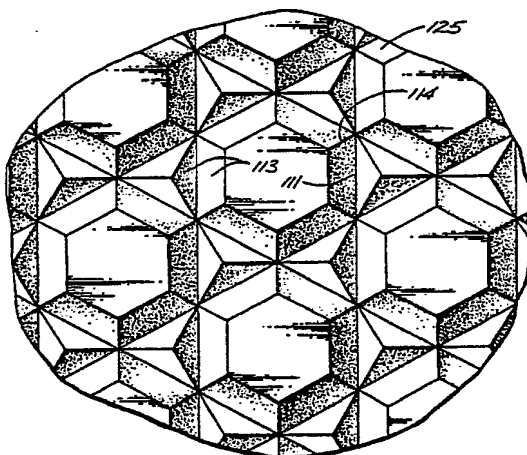
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(54) High efficiency light-emitting diode.

(57) A transparent light-emitting diode has front (14) and back (12) parallel faces and a plurality of side faces (11) perpendicular to the back face. Diagonal faces (13) interconnect each side face (11) with the front face (14) to form a truncated polygonal pyramid surmounting a polygonal base of the light-emitting diode. Because some of the light impinges on the diagonal faces (13) at an angle less than the critical angle for total internal reflection (θ_c), from 1.5 to 2 times as much light is extracted from the LED as a conventional rectangular LED without the diagonal faces. The diagonal faces (13) on the LEDs are readily made by sawing V-shaped grooves in the front face of a wafer (21) on which the LEDs are fabricated.

Fig. 3



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HIGH EFFICIENCY LIGHT-EMITTING DIODE

Field of the Invention

This invention relates to a transparent light-emitting diode with light output up to twice the light output of a conventional light-emitting diode.

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Background of the Invention

In recent years the light-emitting diode (LED) has become a commonplace device for a broad range of applications. In the visible range it may provide communication between an electronic device and the user. In the infrared range it may have broad applications for communications. It may be used in an optical isolator for decoupling an input signal from an output. In many applications it is an important desideratum that the LED emits a large amount of light for a given current.

Transparent LEDs emit light at a p-n junction within the body of semiconductor forming the LED. Light is emitted in all directions from the junction and because of the transparency of the device, light may be emitted from its four sides and its front surface. The back surface is opaque, but some light may be reflected from it and emitted through the sides or front. A portion of the front surface may be occulted by the need for an electrical contact. Thus, light may be emitted from four sides and a portion of the front.

Extracting light from an LED is not easy because of the high index of refraction of the semiconductor material which may be in the range of from about 2.9 to 4.0, depending on wavelength and material. According to Snell's law

$$\sin \theta_c = n_s / n_p$$

only rays that impinge on the chip surface at an angle equal to or less than θ_c will be refracted through the surface. All rays impinging at angles greater than θ_c will experience total internal reflection. In other words, only light emitted from a point source within the chip within a cone of total cone angle $2\theta_c$ having its axis perpendicular to the face of the semiconductor chip will escape from the LED.

Assuming that the index of refraction, n_c , for the semiconductor is 3.3 and the index of refraction, n_p , for a transparent plastic surrounding the semiconductor is 1.5, the critical angle for total internal reflection, θ_c , is 27° . Assuming that the point source of light is isotropic, we find that a fraction, f , of the light flux is within such a cone where f is given by

$$f = \frac{1}{2} (1 - \cos \theta_c) \left[1 - \left(\frac{n_c - n_p}{n_c + n_p} \right)^2 \right]$$

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where the term within the brackets is the correction for Fresnel reflection losses. Where n_c equals 3.3 and n_p equals 1.5, the escape cone contains about 5.2% of the light emitted by the isotropic point source.

LED chips are usually made by a scribe and break technique, resulting in a rectangular parallelepiped where the side faces are smooth crystallographic planes intersecting the front and back surfaces.

An LED chip has six orthogonal surfaces and therefore six possible escape cones. In such a rectangular body reflected rays never change their angle of incidence. In other words, rays emitted in a direction outside of the six escape cones will always remain outside of the escape cones no matter how many reflections they experience. Such rays keep bouncing around within the LED until they eventually are absorbed.

Four of the escape cones directed at the side surfaces are unobstructed. The cone directed towards the back contact surface is partly absorbed and partly reflected towards the front. The cone directed towards the front is partly transmitted through the front and partly occulted and absorbed by the front electrical contact. As a result, in a typical transparent LED light is extracted through only about five cones or approximately 25% of the light generated by the LED is actually emitted.

When the LED is operating in air instead of in transparent plastic, emission is even poorer since the critical angle for total internal reflection is only about 16 to 18° . For this reason it is customary to operate LEDs embedded in transparent plastic for maximum light extraction efficiency.

By making the chip an imperfect rectangular body, for example by sawing the chip instead of cleaving it, somewhat roughened side faces may be obtained. Light is scattered from such roughened surfaces from

non-escape directions into the escape cones. Some light within the escape cones may be internally reflected from a roughened surface. Further, the randomizing of the light directions requires many reflections and because of the non-negligible level of absorption, the long light path within the LED results in only a modest increase in extraction efficiency.

5 Taken to its ultimate or optimal configuration for light extraction, a LED would have a surface of a hemisphere so that light from a small p-n junction in its center is normal to the surface regardless of the ray direction. Such hemispherical LEDs have been built and are highly efficient, but extremely high in price because of the complex processing required. Some of such prior hemispherical LEDs were made by temporarily connecting two LEDs together base-to-base, then tumbling them in a rotating polishing mill until
10 spherical. Alternatively, some of the prior hemispherical LEDs were made by attaching the LED chip to a dop and polishing much as one would polish a lens. The cost of LEDs made by such techniques is prohibitive for most applications.

15 It is, therefore, desirable to provide means for improving the efficiency of light extraction from an LED. It is also desirable that the technique be one easily implemented in manufacturing operations for LEDs without significantly decreasing the yield of LED chips from a wafer of semiconductor.

Brief Summary of the Invention

20 There is, therefore, provided in practice of this invention according to a presently preferred embodiment a transparent light-emitting diode formed of a body of semiconductor material having a flat back face. A plurality of side faces extend perpendicular to the back face. These are surmounted by a plurality of diagonal faces with the number of diagonal faces being the same as the number of side faces. The resulting pyramid is truncated by a front face parallel to the back face. Electrical contacts are made with the
25 back and front faces and a p-n junction within the semiconductor body emits light.

Such an LED may have essentially twelve escape cones, and internal reflections of light which does not escape in the first pass has a reasonable probability of being reflected into an escape cone. This provides an improvement in extraction efficiency of up to twice the light from a conventional LED.

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Brief Description of the Drawings

These and other features and advantages of the present invention will be appreciated as the same becomes better understood by reference to the following detailed description of a presently preferred
35 embodiment wherein:

FIG. 1 is an exemplary transverse cross section of a light-emitting diode constructed according to principles of this invention;

FIG. 2 illustrates in transverse cross section a technique for cutting a semiconductor wafer for forming a plurality of light-emitting diodes;

40 FIG. 3 is a fragmentary plan view of one face of a wafer from which light emitting diodes are cut; and

FIG. 4 illustrates in transverse cross section another embodiment of light-emitting diode.

Detailed Description

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A light-emitting diode (LED) is in the form of a body 10 of semiconductor material such as gallium arsenide, gallium phosphide, $\text{GaAs}_{1-y}\text{P}_y$ or the like. In practice of this invention the LED has a rectangular base with four side faces 11 perpendicular to the back face 12 of the LED. In a typical embodiment the base is square. The base is surmounted by a truncated rectangular pyramid having four diagonal faces 13
50 and a front face 14 parallel to the back face. A portion of the front face has a layer of metal 16 such as aluminum or a gold-germanium alloy for making electrical contact to the LED.

Electrical contact is made to the bottom of the LED by way of a metal layer 17 such as a gold beryllium alloy. Most of the back contact 17 is insulated from the body of semiconductor by an intervening dielectric silica layer 18. The back metal layer makes electrical contact through an aperture in the silica layer to a
55 layer 19 of p-type material in the body of semiconductor which is primarily n-type material. Light is emitted from the resulting p-n junction and is transmitted through the semiconductor material which is transparent to the emitted wave length.

For purposes of description of the improved extraction efficiency, it is assumed that light is emitted

isotropically from a point source in the center of the p-n junction. If each side face subtends an angle from the center of the junction equal to θ_c , a half cone of light will escape through the side face (light at an angle greater than θ_c is internally reflected). The other half of the cone, that is, light emitted towards the back surface, is reflected upward by the dielectric/metal mirror and arrives at the side face at an angle depending on its original direction. In other words, light from the lower half cone with a cone angle of θ_c is transmitted through the side face, resulting in a light flux equivalent to a full cone.

It is preferred that each diagonal face of the truncated pyramid is tilted relative to the side face of the base at an angle in the order of twice the critical angle for total internal reflection, θ_c . Further, the width of the diagonal face from the side face to the front face subtends an angle from the center of the p-n junction in the order of twice the critical angle for total internal reflection. Light within a $2\theta_c$ cone from the assumed point source in the center of the junction will pass through the diagonal face.

Since light emitted toward the back face reflector is reflected forwardly towards the diagonal face, there is a second escape cone through that diagonal face. In other words, there are three escape cones of light transmitted through the two surfaces 11 and 13 on each of the four sides of the rectangular body. Thus there are essentially 12 escape cones which are not significantly affected by metal or contact obstructions.

Light transmitted towards the front contact directly, or indirectly by reflection from the back face, is at least partly occulted by the opaque electrical contact; hence, there is something less than two full cone equivalents emitted through the front face of the LED.

Thus, there are twelve escape cones containing about 62% of the emitted light and two cones centered on the front and back faces containing about 10% of the light that is absorbed. The remaining 28% of the light emitted has a reasonable probability of being reflected into one of the twelve escape cones after one or two reflections on the surfaces of the LED. This probability is enhanced when the diagonal faces are non-specular due to slight roughening during the process of manufacture and there is some scattering of light from the roughened surface. If only one-third of the 28% of light that is outside the escape cones is extracted, the extraction efficiency of the LED is about 70% as compared with about 26% for a conventional rectangular LED. Thus there is a potential improvement in LED efficiency of about 2.7 times.

This efficiency has not been achieved in practice yet. Not all of the light is emitted from the center of the p-n junction. The light emitting area is essentially the entire area of the p-n junction, which typically covers a large fraction of the LED cross section to avoid degradation of the LED at high current densities.

Further, the center of the p-n junction is over the aperture in the silica layer where electrical contact is made. Light emitted toward the back contact is almost entirely absorbed. Although light emitted from areas of the p-n junction above the back contact are absorbed, that contact makes up only about 10% of the p-n junction area.

With an extended light source, the light output of an LED with diagonal faces is in the order of 1.5 the light output of a conventional LED. Such an improvement of 50% of the extraction efficiency can be highly significant.

Although the inclination of the diagonal face and the angles subtended by the faces are in the same order as two times the critical angle for total internal reflection, variations from such dimensions are appropriate as the area of the p-n junction increases. It turns out that with a p-n junction that extends all the way across the back face of the LED, an angle between the diagonal face and the side face in the range of from 30 to 60° is appropriate, with good results being obtained with an angle of 45°.

Thus, in an exemplary embodiment an LED may be 300 micrometers square and have a total height of 200 micrometers. The height of the side faces is 100 micrometers and the diagonal faces extend at an angle of 45° relative to the side faces. Tests of light-emitting diodes with diagonal faces in the range of from 30 to 60° from the side faces show improvements in light extraction efficiency of from one and one-half to two times the light output of a conventional LED of similar dimensions without the diagonal faces.

Fabrication of a LED with beveled edges is a straightforward adaption of conventional manufacturing techniques for semiconductors. LEDs are conventionally made in substantial numbers on a wafer of semiconductor. Very light scratches may be scribed on a face of the semiconductor to provide a crack initiator. When broken, the individual LEDs are cleaved from each other along crystallographic planes extending from the scribe lines. Alternatively, the LEDs are sawed from the wafer with a diamond dicing saw.

To make a beveled LED, an array of parallel V-shaped grooves are sawed into one face of a wafer by a nearly conventional diamond dicing saw. The dicing saw perimeter is dressed with a V-shaped face to produce diagonal faces 13 on adjacent LEDs to be separated from the wafer. The depth of the saw cut is controlled to define the desired width of the diagonal faces.

After sawing arrays of parallel V-shaped grooves in orthogonal directions, the individual LEDs may be separated from each other by cleaving from the bottom of the groove, or a second pass may be made with

a conventional dicing saw aligned with the bottom of the groove to cut the balance of the distance through the wafer. In still another alternative the face of the dicing saw may be dressed so that the V-shaped groove and the parallel-sided cut through the balance of the wafer are made in a single pass of the dicing saw. After sawing, the sawed surfaces are etched for removing the highly absorbing saw damaged material adjacent to the surface.

It will be noted that cleaving produces side faces 11 of the LEDs which are substantially specular. The diagonal faces are slightly roughened due to the diamond particles in the dicing saw. The side faces are also slightly roughened when the LEDs are separated from each other by sawing. The resultant non-specular reflection of light from such faces slightly enhances efficiency of light extraction from the LED.

The square LED with beveled edges hereinabove described is a better approximation of a hemispherical than the rectangular parallelepiped of a conventional LED. A still better approximation of a hemispherical external shape is provided by a sawing pattern as illustrated in FIG. 3 which is a plan view of a fragment of a wafer with an array of V-shaped grooves cut in the front surface for separating individual LEDs from each other. As illustrated in this embodiment, each LED has a hexagonal front face 114 and six diagonal faces 113 adjacent six side faces 111 of the LED. The diagonal faces on the several LEDs on the wafer are defined by sawing a plurality of V-shaped grooves 125 at 60° from each other in the front face of the wafer.

The individual LEDs may then be separated from each other by cleaving from the bottom of the grooves or by extending a dicing saw cut clear through the wafer as hereinabove described. The latter technique is preferred since the crystal structure of the semiconductor does not lend itself to crystallographic cleavage at 60° angles and there is no problem in removing the triangular scraps between adjacent LEDs. It will be noted that because of such scraps the yield of hexagonal LEDs from a wafer is two-thirds of the yield of rectangular LEDs. The enhanced light extraction efficiency through twelve faces as compared with eight faces in the rectangular embodiment may offset the added cost due to decreased yield.

FIG. 4 illustrates in transverse cross section another embodiment of LED for high efficiency light extraction. This LED has side faces 211 and a back face 212 similar to the embodiments hereinabove described. It differs, however, in that one of the diagonal faces 213a is at a different angle from its adjacent side face 211 than the angle between the opposite side face 213b and its adjacent side face. A similar asymmetry is provided for the other two diagonal faces not illustrated in the drawing. As a result of this asymmetry, the front face 214 is shifted diagonally toward one corner of the LED.

The angular difference between the opposite faces is only a few degrees so that there is little degradation of the light extraction efficiency due to an exit cone of light illuminating an area off of a diagonal face. Substantial degradation may be avoided by choice of dimensions of the side faces and diagonal faces. However, extraction efficiency of light internally reflected within the LED is enhanced due to the asymmetrical reflections from the diagonal faces.

Such an embodiment with asymmetrical beveling is easily made by the technique described hereinabove by simply dressing the face of the dicing saw with the desired asymmetry, thereby producing an asymmetrical V-shaped groove.

Although limited embodiments of light-emitting diode constructed according to principles of this invention have been described and illustrated herein, many modifications and variations will be apparent to those skilled in the art. Thus, for example, in the illustrated embodiments the p-n junction is quite near the back face of the LED. It may be desirable to employ a LED where the p-n junction is an appreciable distance above the back face. In such an embodiment it is preferable that the height of the side faces should subtend an angle above the center of the junction in the order of the critical angle for total internal reflection. Thus, half of the light in the exit cone is above the plane of the junction and some of the light may exit the side face below the plane of the p-n junction.

It will also be apparent that other polygonal shapes such as triangular or octagonal LEDs may be provided in practice of this invention. It is, therefore, to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

Claims

1. A transparent light-emitting diode comprising:

a back junction (17);

a front electrical contact (16); and

a body (10) of transparent semiconductor between the back junction and the front electrical contact, the body being in the form of a polygonal base (11) surmounted by a truncated polygonal pyramid (13).

2. A light-emitting diode according to claim 1 wherein the base is rectangular with side faces (11)

perpendicular to the back junction (17) and the pyramid (13) is a rectangular pyramid.

3. A light-emitting diode according to claim 1 or 2 wherein the angle between a face (13) of the pyramid and a side face (11) of the base is from 30 to 60°.

4. A light-emitting diode according to claim 3 wherein the angle between a face (13) of the pyramid and a side face (11) of the base is in the order of twice the critical angle for total internal reflection (θ_c).

5. A light-emitting diode according to any of claims 1 to 4 wherein the width of a face (13) of the pyramid from a side face (11) of the base to the front (14) subtends an angle from the center of the back junction in the order of twice the critical angle for total internal reflection (θ_c).

6. A light-emitting diode according to any of claims 1 to 5 wherein the height of a side face (11) of the base above the junction (17) subtends an angle from the center of the junction (17) in the order of the critical angle for total internal reflection (θ_c).

7. A light-emitting diode according to any of claims 1 to 6 wherein the pyramid (213) is asymmetrical.

8. A light-emitting diode according to any of claims 1 to 7 wherein the angle between a side face (211) of the base and a face (213a) of the pyramid on one side of the light-emitting diode is different from the angle between a side face (211) of the base and a face (213b) of the pyramid on the opposite side of the light-emitting diode.

9. A method for making a light-emitting diode comprising the steps of:

forming a wafer (21) of semiconductor with doped regions for forming a plurality of light-emitting diodes;

sawing a first array of parallel V-shaped grooves (13,13) in a front face of the wafer;

20 sawing a second array of parallel V-shaped grooves (13,13) in the front face of the wafer intersecting the first array of grooves; and

separating individual light-emitting diodes from each other along planes (11) perpendicular to faces of the wafer (21) and extending from the bottoms of the V-shaped grooves (13,13) through the wafer for producing light-emitting diodes with beveled edges.

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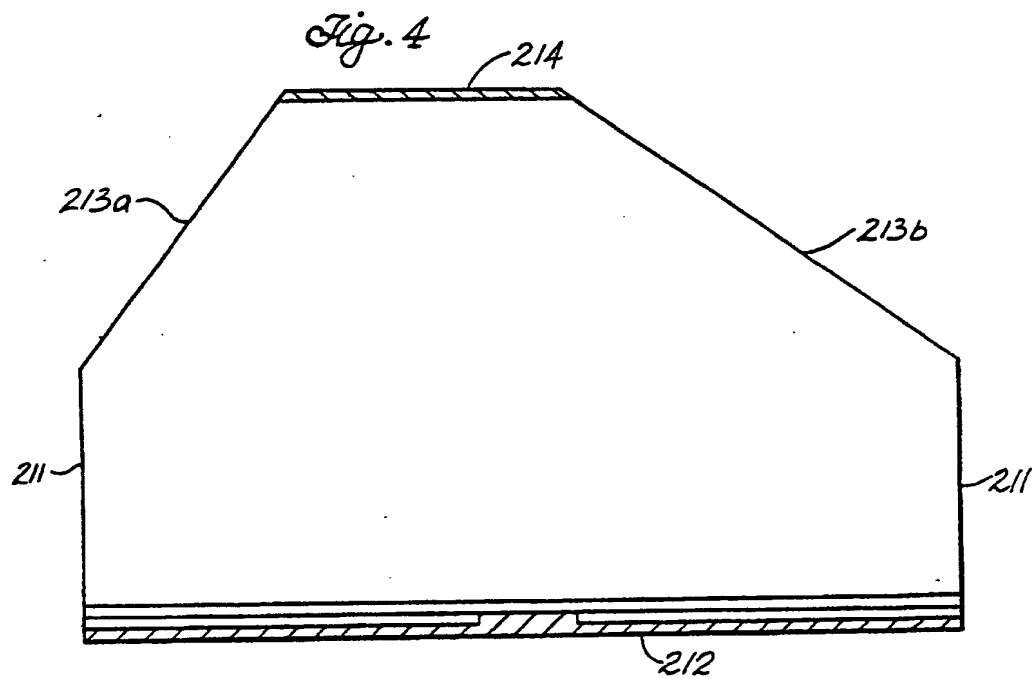
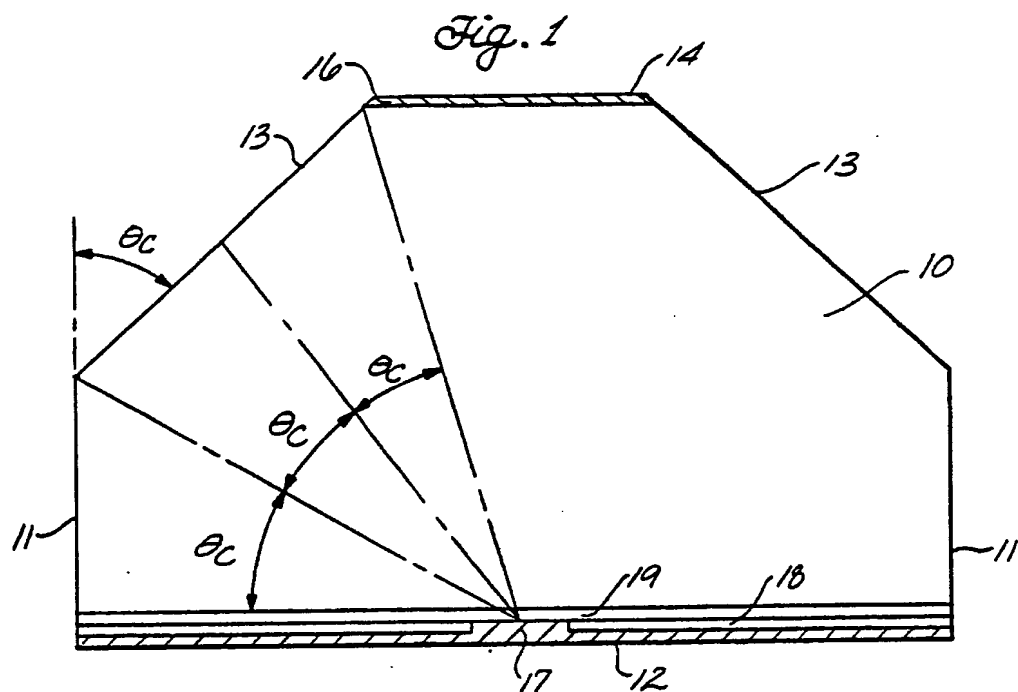


FIG. 2

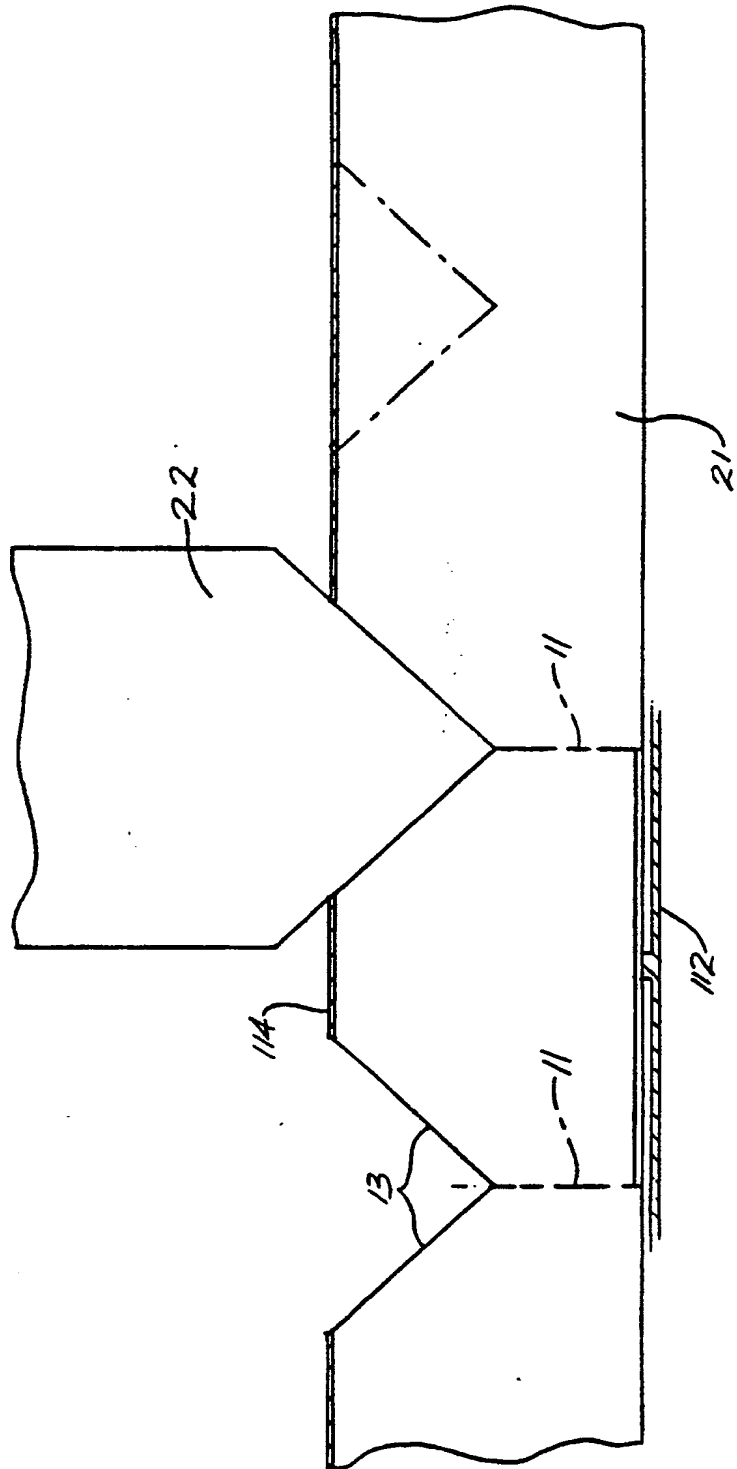


Fig. 3

